Catastrophic, Non-Linear Inundation from Sea Level Rise and its Policy Implication

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The 2007 IPCC [1] report projects a global sea level rise of 0.18─0.59 m by 2100 due to climatic changes. Recent studies on ice disintegration in the Greenland and West Antarctic ice sheets [2-5] and paleoclimatic changes [6] suggest that the IPCC report may greatly underestimate the role of accelerated ice dynamics on sea level rise. Alternative estimates indicate that sea level could rise by 1.4 [7] ─ 5 m [8] by 2100. Such large sea level rises in this century would threaten millions of people in coastal areas. Studies of sea level rise impacts [9-12] typically delineate inundation zones by projecting future sea levels on digital elevation models (DEM). However, few studies have quantified the effects of inundation processes on sea level rise impacts due to poor vertical resolution (>1.5 m) of DEMs [7]. By analyzing DEMs derived from airborne light detection and ranging (LIDAR) measurements for South Florida, USA, here we show that inundation processes are non-linear: inundation is gradual before reaching a threshold, and speeds up rapidly afterwards due to the regional topography. Accelerated sea level rise will cause the threshold to be reached sooner by amplifying non-linear processes, and must be considered in policy-making.

South Florida is one of the most vulnerable areas in the world to inundation caused by sea level rise due to its gently-sloped topography with vast areas only a few meters above the current sea level. At the center of the region is the Everglades─the largest wetland system in North America. It occupies a topographic trough with a width of 50─60 km, providing a pathway for sheet water flow fed by an upstream watershed and Lake Okeechobee (Fig. 1). The east side of the Everglades is bounded by the Osceola Plain with a width of 30 km and elevation of 5─9 m and the Atlantic Coastal Ridge (ACR) with a width of 5─10 km and elevation of 4─6 m, while the west side is bounded by another topographic high, the Immokalee Rise [13]. Streams and swales cutting through the ACR in a perpendicular direction discharge the water from the Everglades into the Atlantic Ocean.

The majority of the population and dwellable real estate in South Florida are located on the ACR and adjacent areas in Palm Beach County (PBC), Broward County (BC), and Miami-Dade County (MDC). The total population, property, and gross product of the three counties are about 5 million, \$833 billion, and \$169 billion, respectively, based on the 2000 census, 2007 property tax data, and 2003 state economic statistics. These values represent more than 30% of the totals for the State of Florida which has 67 counties, making the three counties a center of Florida's society and economy. Also, the federal and state governments have initiated an ambitious \$8 billion plan to recover the Kissimmee-Okeechobee-Everglades ecosystem in the next 30 years by restoring the sheet flow that has been severely disrupted by past human activities. Recent advances in LIDAR technology enabled mapping of 2,300 km^2 of Atlantic coastal areas vulnerable to storm surge flooding in the three counties utilizing more than 3.2 billion point measurements with a 0.15 m vertical accuracy [14]. A DEM with a cell size of 30 m for South Florida was generated by combining LIDAR data with U.S. Geological Survey collected elevation data for the Everglades. Elevations were referenced to NAVD88, which is approximately equivalent to the daily mean higher high water. The high level of elevation accuracy of the DEM allowed a detailed analysis of the inundation process. Statistics of inundated land areas, population, and property values for projected rising seas indicate that MDC is most vulnerable to inundation, followed by BC and PBC, consistent with the general trend in topography (Fig. 1).

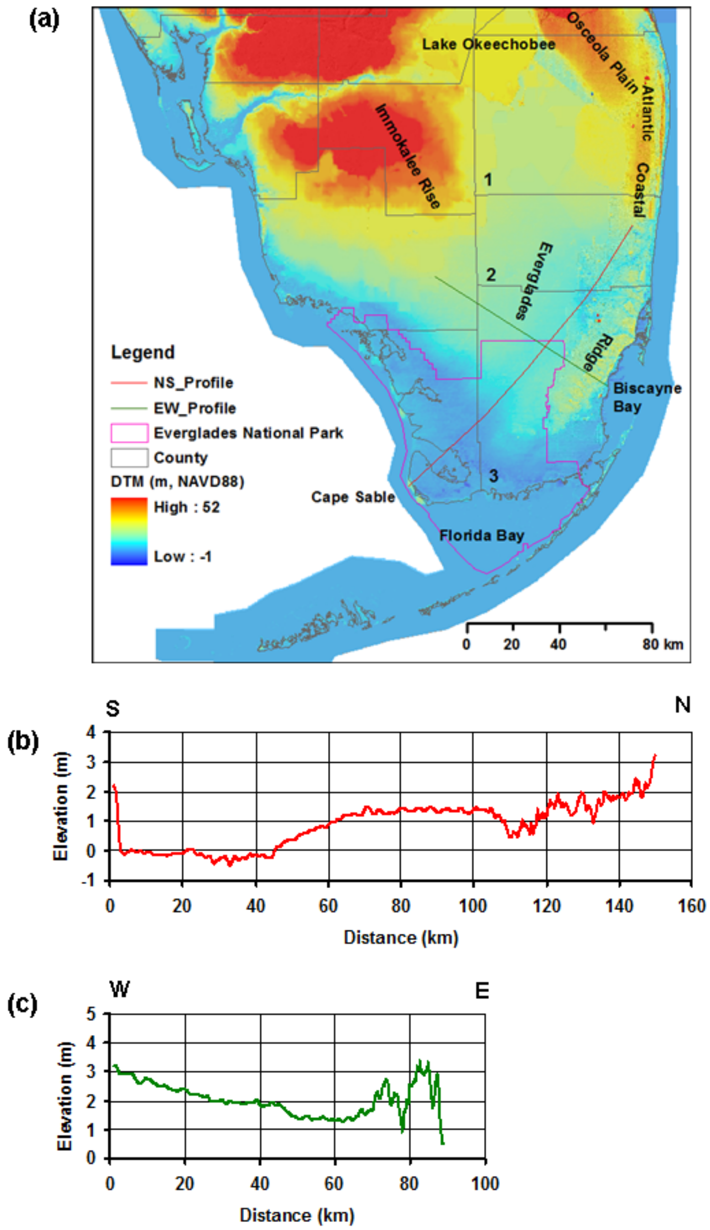

Fig 1. The topography of south Florida (a), the elevation profile through the Everglades along the northeast–southwest direction (b), and the elevation profile across the Everglades along the northwest–southeast direction (c). 1: Palm Beach County (PBC), 2: Broward County (BC), and 3: Miami Dade County (MDC) in (a). The elevation values along the profiles were derived by first sampling the merged 30 m DEM every 30 m and then smoothing samples using a moving average method with a window of 11 points. Note: once the sea level rises 1.5 m above its current level, there is no topographic high along the profile (b) that can block saltwater of the Gulf of Mexico from inundating western portions of MDC and BC. The profile across the Everglades indicates that the lowest portions of the trough are closer to the ACR on the east than to the Immokalee Rise on the west.

A 0.5 m sea level rise will allow saltwater from the Gulf of Mexico to inundate large areas in Everglades National Park and marsh areas in southeastern MDC (Fig. 2a). Several areas on barrier islands and the mainland with low elevations east of the ACR will be inundated by the Atlantic Ocean. Although some populated areas and expensive residential houses and condominiums at the edges of barrier islands and the mainland are influenced, sea level rise will only inundate less than 0.6% of MDC's population and property, the most impacted of the three counties. The impact of inundation on population and property can be mitigated by preventing saltwater flooding through the canals. However, saltwater intrusion to the freshwater aquifer and disruption of infrastructure by increased surge flooding will make it difficult to maintain a modern standard of living in coastal areas.

A 1 m sea level rise will inundate many areas on barrier islands along the Atlantic coast from the lagoon side and the low elevation areas east of the ACR. Large areas of low-lying lands west of the ACR in southern BC and northern MDC will be below sea level (Fig. 2b). These inland areas are occupied by many fragmented local topographic highs, but still are separated from the directly inundated coastal area by thin linear features such as highways with higher elevations. It would be extremely challenging to protect these low-lying inland areas from increased storm surge flooding by enhancing these thin separators, and to maintain habitability, given the reduced freshwater supply resulting from saltwater intrusion into the porous limestone and sand of the surficial Biscayne aquifer.

A 1.5 m sea level rise will cause calamitous inundation throughout South Florida. The majority of barrier islands and mainland low elevation areas east of the ACR are inundated by the Atlantic Ocean. Saltwater reaches the western portion of MDC and southern BC from the Gulf of Mexico by flooding through the Everglades trough (Fig. 2c). About 58% of the land area of MDC is inundated directly by saltwater, altering the southern ACR into a chain of islands similar to the Florida Keys. Although this sea level rise only causes a direct inundation of 14% and 20% of MDC's population and property, the drastic reduction in land area, exacerbated storm surge flooding, and saltwater intrusion will make it impossible to support the entire population living on the remaining high ground. By contrast, PBC will not be inundated significantly by the 1.5 m sea level rise.

Inundation appears to accelerate for equal increments of sea level in comparisons of inundated areas for 0.5 m, 1 m, and 1.5 m sea level rises. To examine changes in inundation process, hypsometric curves [15], which delineate the distribution of inundated land area, population, and property at different elevations, were created for three counties utilizing 33 elevation intervals from 0 to 8 m. All hypsometric curves have an S-shape, indicating that a majority of land areas are located in a band of mid-level elevations (Fig. 3). As a result, in low, middle, and high elevation zones, inundation will occur slowly, fast, and slowly, respectively, in response to a constant rate of sea level rise. Population and property hypsometric curves based on elevation intervals exhibit a similar non-linear behavior, but with considerable differences in inundation processes. Thresholds, i.e., elevations beyond which inundation accelerates rapidly, are identified at 1.25 m, 1.5 m, and 3 m elevation in MDC, BC, and PBC, respectively. The land area inundated as sea level rises from 0 to 3 m elevation in PBC, and from 0 to 1.5 m in BC, are about 5% of each county's area, while the land area flooded between 3 and 5 m in PBC and between

1.5 and 3 m in BC are 75% and 79% of each county's area, respectively. In MDC, about 11% of the land area, most of which is located in Everglades National Park, is already below 0 m elevation. Changes in flooded land areas before and after the elevation threshold in MDC are less dramatic than in the other counties, because of the considerable area already below the elevation threshold. The inundated land area between 0 and 1.25 m is about 27% of MDC's area, while the inundated land area between 1.25 and 2.25 m is about 50% of the county's area.

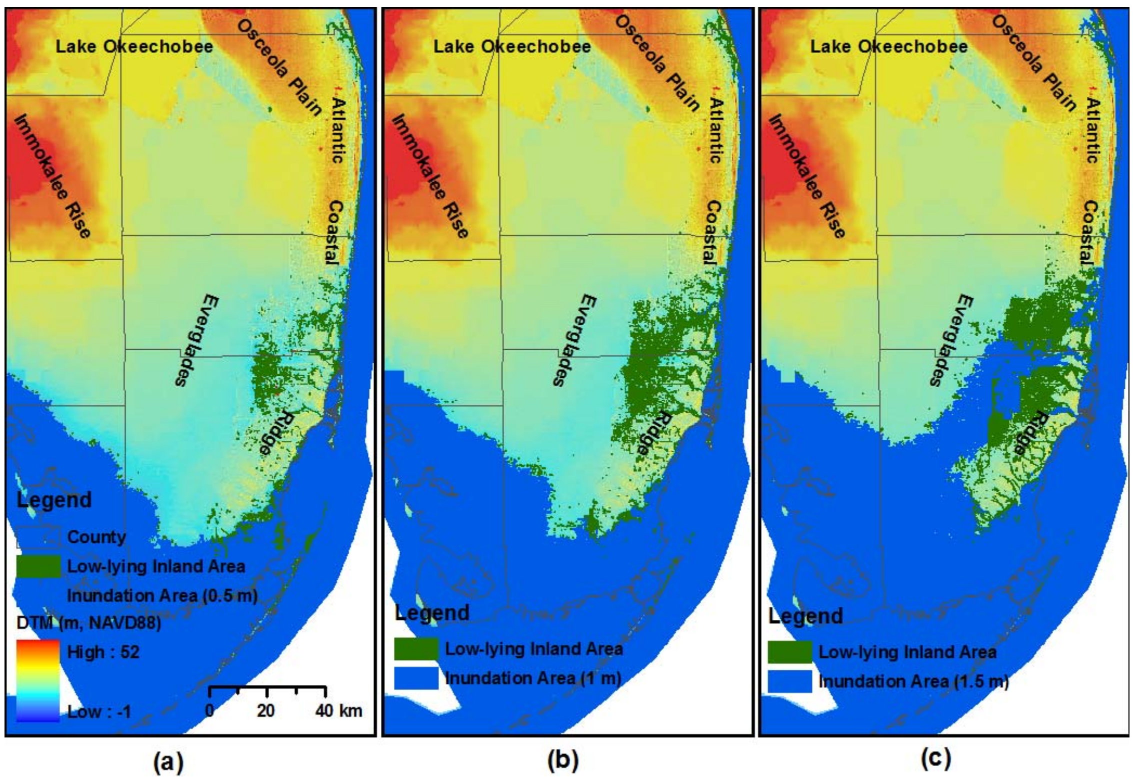

Fig. 2. The inundation map for south Florida with (a) 0.5 m, (b) 1 m, and (c) 1.5 m sea level rises. Sea level is referenced to NAVD88 vertical datum. *Inundation Area* represents land areas inundated directly by the projected rising sea, while *Low-lying Inland Area* delineates areas which are below the projected rising sea, but are separated from the *Inundation Area* by elevation barriers.

The effect of acceleration in sea level rise on inundation was analyzed by assuming that sea level will rise in a quadratic form in the future. Accelerated sea level rise in the next century further amplifies the non-linear inundation process as shown in Fig. 4. The faster sea level rise accelerates, the sooner the inundation threshold is reached. For PBC, the inundated areas for scenarios of 2.5 and 3 m sea level rise by 2100 comprise less than 5% of the county; however, under these same scenarios, 34% and 54% of the county's area would be inundated by 2120. The increases in inundation areas in BC for six scenarios of sea level rise are gradual before 2070. The thresholds of inundation processes occur between 2070 and 2120 for scenarios of sea level rise from 1 to 3 m, respectively. For these scenarios, the inundation proceeds with gathering pace after the threshold is reached as inundated areas increase from 5% to 32% within 10 to 20 years. Rapid inundation in MDC will start between 2060 and 2090 for scenarios of sea level rise from 1.5 to 3 m.

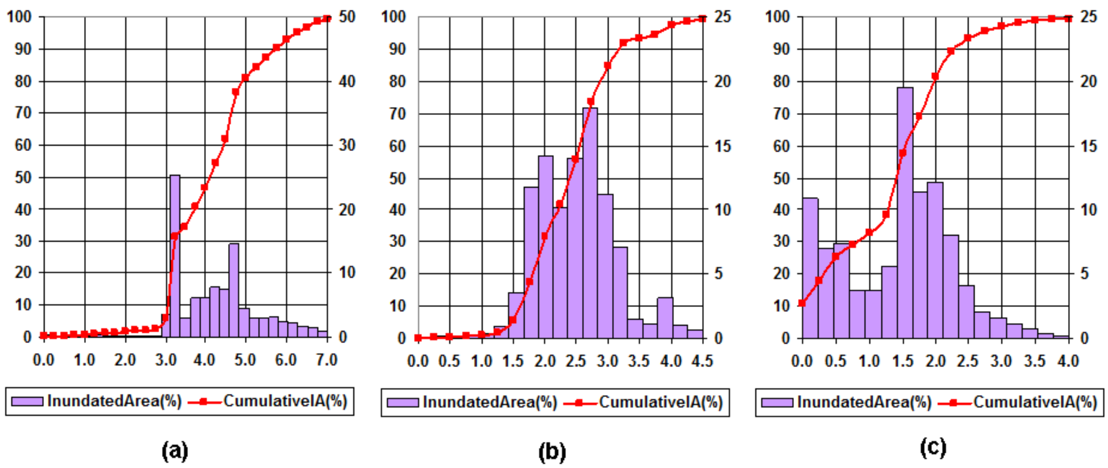

Fig. 3. Land area hypsometric curves for elevation in Palm Beach County (a), Broward County (b), and Miami-Dade County (c). *X* axis represents the elevation (m) above the NAVD88. *Y* axis on the left side is for variable *CumulativeIA* and *Y* axis on the right side is for variable *InundatedArea*. *CumulativeIA*: Land areas below a given sea level (elevation) as a percentage of the county's area, and connecting with the ocean as sea level rises. *InundatedArea*: Histogram for land areas between two adjacent elevations as the percentage of the county's area. The land areas of Palm Beach, Broward, and Miami-Dade Counties are about 5800 km^2, 3200 km^2, and 5100 km^2, respectively.

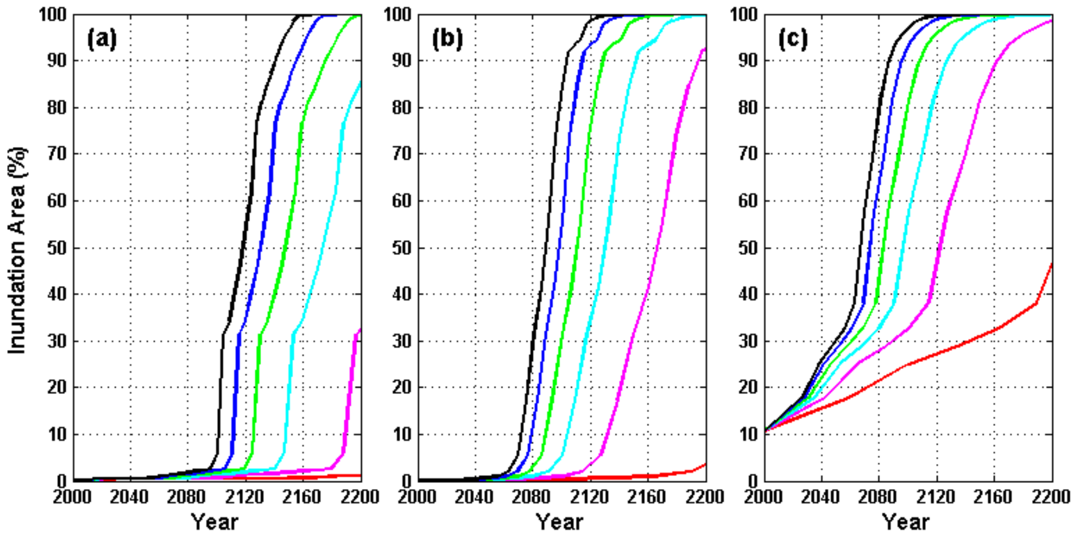

Fig. 4. Land area hypsometric curves for time for scenarios of 0.5 m (red), 1 m (purple), 1.5 m (light blue), 2 m (green), 2.5 m (blue), and 3 m (black) sea level rise by 2100 in Palm Beach County (a), Broward County (b), and Miami-Dade County (c).

There remains large uncertainty in projections of sea level rise for this century, ranging from 0.18 to 5 m because of our limitation in understanding the effects of global warming. As demonstrated by the case of South Florida, this uncertainty poses a great challenge for implementation of a policy to cope with the impact of sea level rise on the coastal environment. A 0.18 m sea level rise by 2100 does not cause a significant impact on South Florida, and a gradual change from the current policy is appropriate to handle this scenario. In contrast, sea level rise of 1.5 m or more by 2100 is catastrophic for MDC and BC and a drastic change in policy is needed. A strategic plan for shifting the economic core and population from South Florida to higher elevation areas in central and northern Florida has to be implemented. The objectives of the comprehensive Everglades restoration plan also have to be adjusted or even abandoned for the high-end scenarios of sea level rise.

Both the public and government agencies are understandably reluctant to take action to reduce the impact of future sea level rise unless direct and dramatic events actually occur. The large uncertainty in projection of future sea level rise further increases this reluctance. However, if society is waiting for the arrival of extensive and direct evidence of accelerated sea level rise impacts before response, non-linear inundation processes clearly show the danger of this approach. The slow inundation process occurring prior to the threshold can give people the false impression that sea level rise does not cause serious problems, whereas the rapid inundation after the threshold limits the adequacy of a late response as demonstrated by the case of South Florida. Construction of dikes to protect low-lying areas from saltwater intrusion is extremely difficult in BC and MDC due to the highly porous limestone and sand of the ACR. In addition, as of 2000, approximately 4 million people resided in BC and MDC. The population increased 29% and 16% from 1990 to 2000, respectively, and is expected to grow even more in the future. Changing policy to reverse this trend of population growth and the relocation of millions of people requires time and resources.

The non-linear inundation process and the amplification by accelerated sea level rise is not unique to South Florida, and may be a characteristic of other low relief coastal areas such as the Mississippi delta, the Chesapeake Bay, and the Pamlico-Albemarle Peninsula of North Carolina. To mitigate the societal impacts of the non-linear inundation process in these low-lying areas, detailed monitoring, mapping, and modeling of sea level impacts, research on the human carrying capacity and resiliency of limited high land areas, and comprehensive planning for relocating population, economic foci, and endangered species in response to various scenarios of sea level rise need to be undertaken properly.

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